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Advanced Materials for Mercury 50 Gas Turbine Combustion System

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Outline

- Project Description and Goals/Objectives
- Project Team/Partnerships
- Task Definition and Activities Planned
- Milestones Completed and Planned
- Key Technical Barriers and Strategies to Overcome
- Project Risks
- Impact of Project on Goals of the Distributed Energy Program
- Summary

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Project Description & Goals/Objectives

- Improve Mercury 50 Advanced Combustion System Durability
  - Goal: 30,000 hours / 3,000 cycles
- Reduce Life Cycle Cost
- Minimize Performance & Engine/Package Design Impact
- Maintain Single Digit Emissions
- Combustor Liner and Fuel Injector Tip Applications
- Advanced Materials Technologies
  - Improved Thermal Barrier Coatings (TBCs)
  - Oxide Dispersion Strengthened (ODS) Alloys
  - CFCC Liner with Environmental Barrier Coatings
  - Monolithic Ceramics
- 4000-Hour Engine Demonstration at End User Site
- Expand Technologies to Other Gas Turbine Engines

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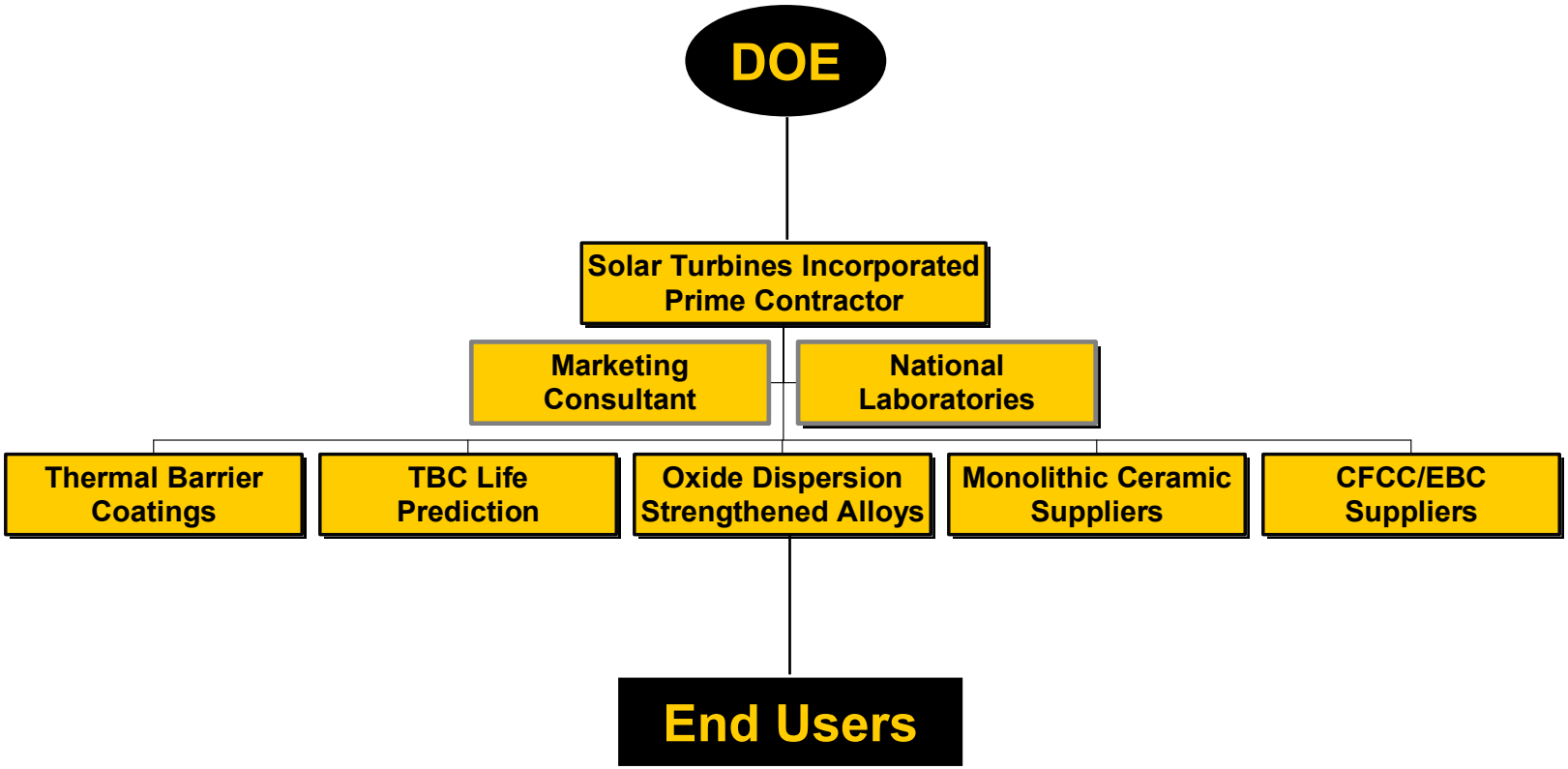
The Development Team



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The Development Team

- **Program Sponsor**
  - **U.S. Department of Energy (DOE)**
    Office of Distributed Energy, Washington, DC
    - **Debbie Haught, Merrill Smith**

- **DOE Project Management**
  - **DOE Chicago Operations Office, Argonne, IL**
    - **Dale Dietzel, Steve Waslo**
  - **DOE Golden Field Office, Golden, CO**
    - **Paul Bakke**

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The Development Team

- **Marketing Consultant**
  - Onsite Energy, Keith Davidson
- **Thermal Barrier Coating Suppliers**
  - Solar Turbines Incorporated
  - United Technologies Research Center
  - University of Connecticut
  - Praxair Surface Technologies, Inc.
  - The Welding Institute
- **TBC Life Prediction**
  - Research Applications, Inc.
- **Oxide Dispersion Strengthened Alloys**
  - Schwarzkopf Technologies Corporation
  - Special Metals Incorporated

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The Development Team

- CFCC Liner Suppliers
  - Goodrich Corporation
  - GE Power Systems Composites
  - COI Ceramics/Siemens Westinghouse
- Environmental Barrier Coatings
  - United Technologies Research Center
- Monolithic Ceramic Suppliers
  - Honeywell Ceramic Components
  - Kyocera Industrial Ceramics Corporation
- Materials Characterization
  - Oak Ridge National Laboratory
- Nondestructive Evaluation
  - Argonne National Laboratory

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Task Definition & Activities Planned

- **TASK 1 : Preliminary Concept Design and Evaluation**
  - **Task 1A: CFCC Combustor Liner Durability Testing**
- **TASK 2 : Sub-Scale Testing (Single Injector Rig)**
- **TASK 3 : M50 Engine Adaptation to Accept Modified System**
- **TASK 4 : Full-Scale Hardware Tests (Rig and Engine Tests)**
- **TASK 5 : Field Evaluation (4,000 hours)**

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Improved Liner Durability

- High thermal resistance TBC systems
  - Thicker TBC systems
  - TBC systems with lower thermal conductivity
- High-temperature superalloys
  - Y_2O_3 oxide dispersion-strengthened (ODS)
- Continuous fiber-reinforced ceramic-matrix composite (CFCC)
  - Environmental barrier coating (EBC)
  - Lower cost ceramic fibers
  - CFCC durability testing in Centaur 50 engine

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Advanced TBC Development - Task 1

- TBC Coating Systems evaluated through isothermal cyclic furnace testing
  - Solar Baseline 25 mil YSZ TBC
  - Multiple Solar Deposited 40 mil YSZ TBCs
  - Praxair 40 mil dense vertically cracked YSZ TBC
  - United Technologies 40 mil YSZ TBC
  - United Technologies 20 mil YSZ TBC (low thermal conductivity system)
  - UCONN Solution Plasma Sprayed TBC
  - 25 mil Low thermal expansion TBC (UCONN/Solar)
- Solar TBC system down-selected based on cyclic testing results

Thermal Barrier Coating System	2000°F 10 hr cycles	2100°F 10 hr cycles
Solar 25 mil Baseline	350, 377	106, 108
Solar 40 mil Advanced TBC	542, 558, 560	196, 201, 212

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Advanced TBC Development - Task 1

- Completed TBC thermal conductivity study (ORNL)
  - Ceramic coupons aged isothermally
    - Temperature dependence (1800°F - 2400°F)
    - Time dependence (As-sprayed - 5,000 hours)
  - Density and thermal diffusivity measured
  - Thermal conductivity calculated for exposure time and temperature
  - Results used for design and life prediction
- Completed TBC life prediction for advanced TBC
  - Over 30,000 hour life predicted for advanced TBC
    - Cyclic testing
    - Microstructural characterization
    - Thermal conductivity study

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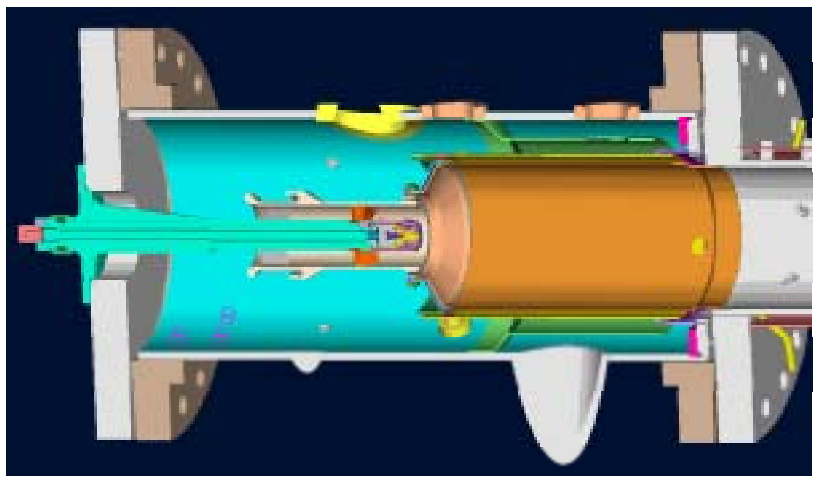
Advanced TBC Rig Testing - Task 2

- Completed baseline 25-mil TBC single injector (SI) rig thermal paint test
  - SI rig test parameters consistent w/ M50 operating parameters
  - Thermal paint temperatures consistent with thermocouples
  - 360° uniform temperatures (± 50 degrees)
- Down-selected Advanced 40 mil TBC scheduled for test by year end



SI Rig

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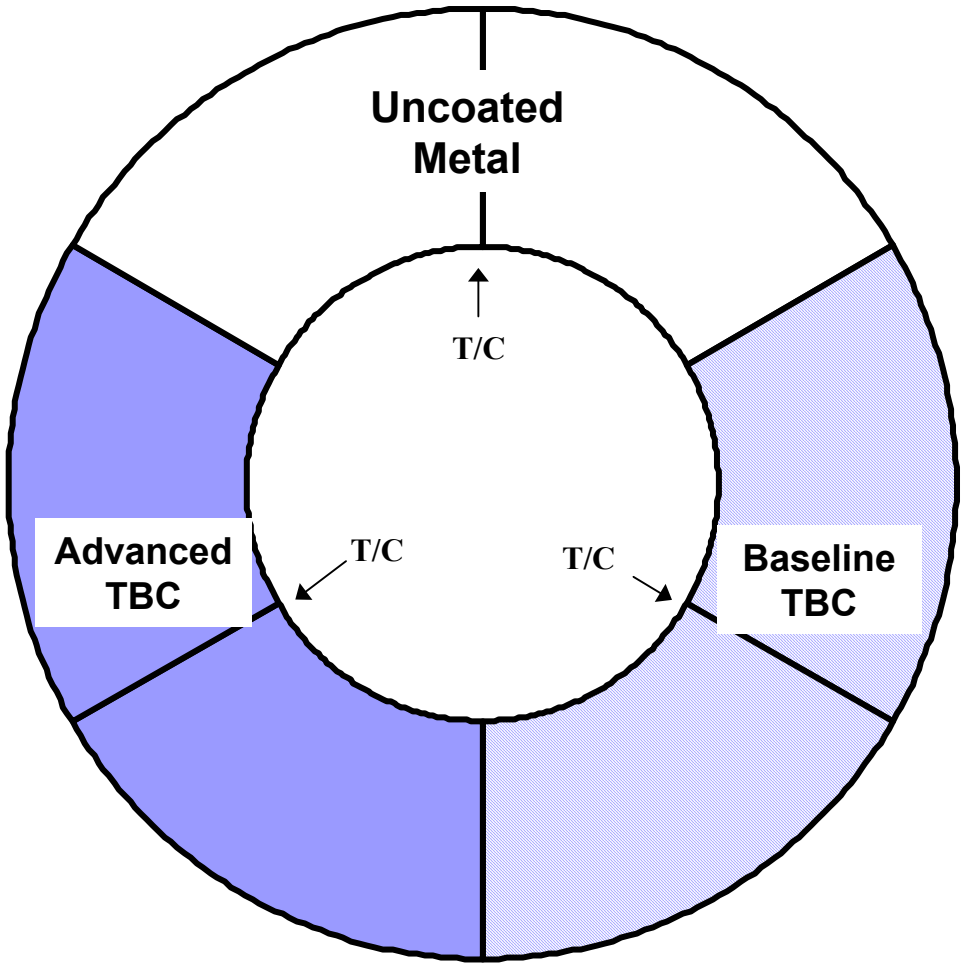
Advanced TBC Rig Testing - Task 2

TBC " Rainbow" Test



SI Liner with Thermal Paint

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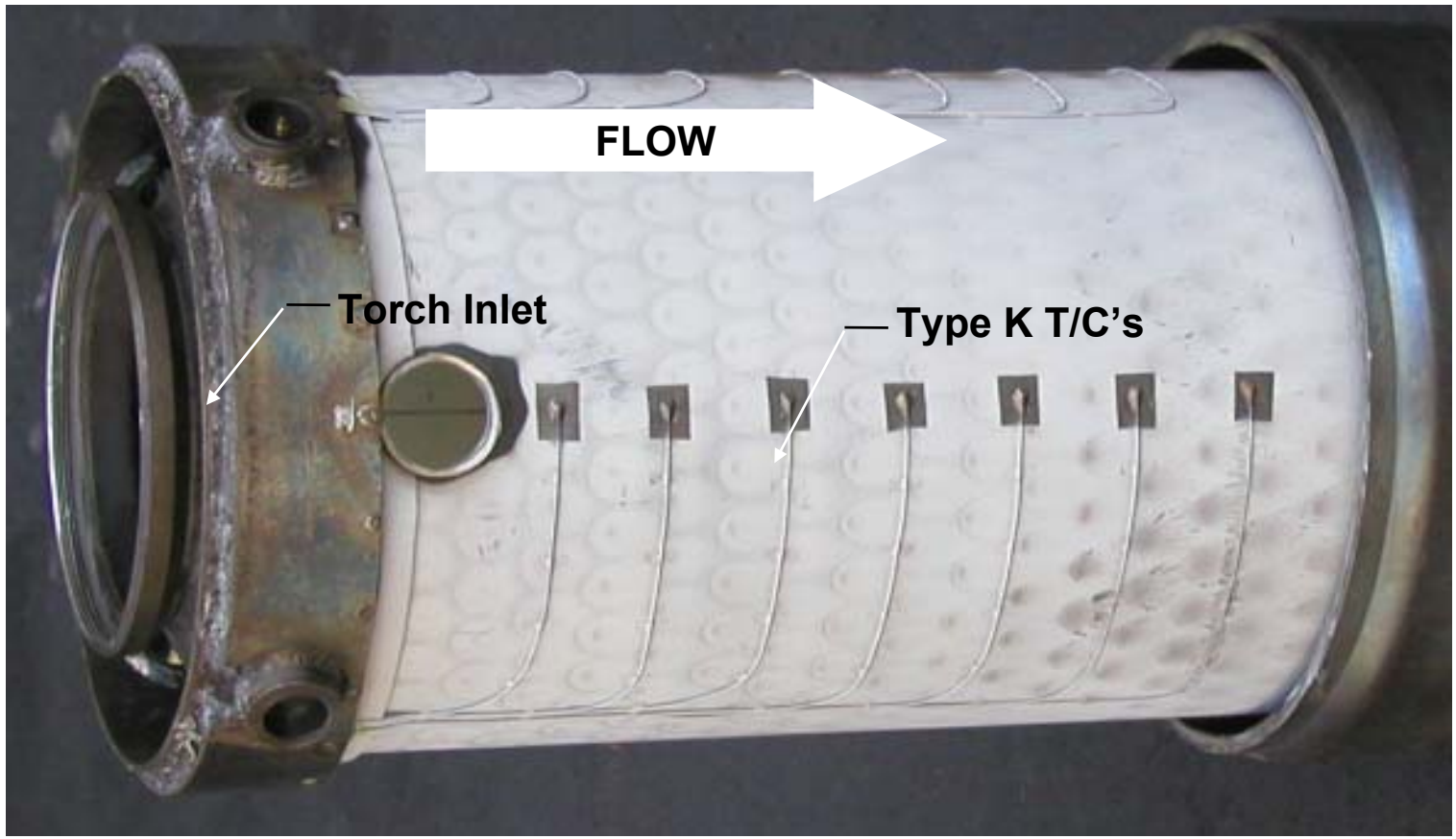
Advanced TBC Rig Testing - Task 2



Single-Injector Rig Inner Liner
25-mil Baseline TBC Thermal Paint Test

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Advanced TBC Turbine Modifications - Task 3

- **No engine adaptations or control system modifications are required for the 40 mil Advanced TBC system**

- **Subtask B Topical Report**
  - **Commercialization Plan submitted in Sept. 2003**

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Advanced TBC Full Scale Testing -Task 4

- **1000-hour full-scale engine Test of 40 mil thick Advanced TBC**
  - **Completed initial TBC 200-hr engine test, 50 cycles**
  - **Mercury 50 S/N 002**
  - **Solar developmental test cell**
  - **TBC remained in excellent (as sprayed) condition**
  - **Liner will continue testing for 800+ hours**

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Improved Injector Tip Durability

- Monolithic ceramic, silicon nitride (Si_3N_4)
  - Need proven environmental barrier coating
- High-temperature superalloy
  - Y_2O_3 oxide dispersion-strengthened (ODS)

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ODS Injector Tip Development -Task 1

- **Yttria Oxide Dispersion Strengthened**
  - **Fe-based substrate: MA 956**
  - **Ni-based substrate: MA 754**
- **Exceptional high-temperature strength and creep resistance**
  - **Coarse and highly elongated grains**
  - **Fine dispersion of stable hard particles**
- **Joining is a serious problem**
  - **Traditional methods destroy elongated grain orientation and agglomerate particles**
  - **Strength reduced up to 65% from welding**

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ODS Injector Tip Development -Task 1

- Initiated validation of ODS MA 956 extruded bar material properties
  - Successful joining achieved by brazing concentric ring test samples and simplified injector tip
  - Initial laser welding trials made on ODS concentric ring samples
  - Brazed injector tip assembly showed visible cracks as received - exacerbated with machining and joining operations
  - MA 956 supplier Special Metals engaged in diagnosing potential material processing problem
- Suspended design, fabrication, and testing of injector tips pending resolution of material performance
  - Alternate materials (MA754) /suppliers (Plansee) under evaluation

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CFCC Durability Testing -Task 1A

10 Field Installations

- More than 59,000 Total Hrs of Full-Load Field Operation
- Over 15,000 hrs on single set of liners with EBC
- ChevronTexaco Exploration & Production, Bakersfield, California
- Malden Mills Industries, Lawrence, Massachusetts
- Reduced Emissions

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CFCC Durability Testing - Task 1A

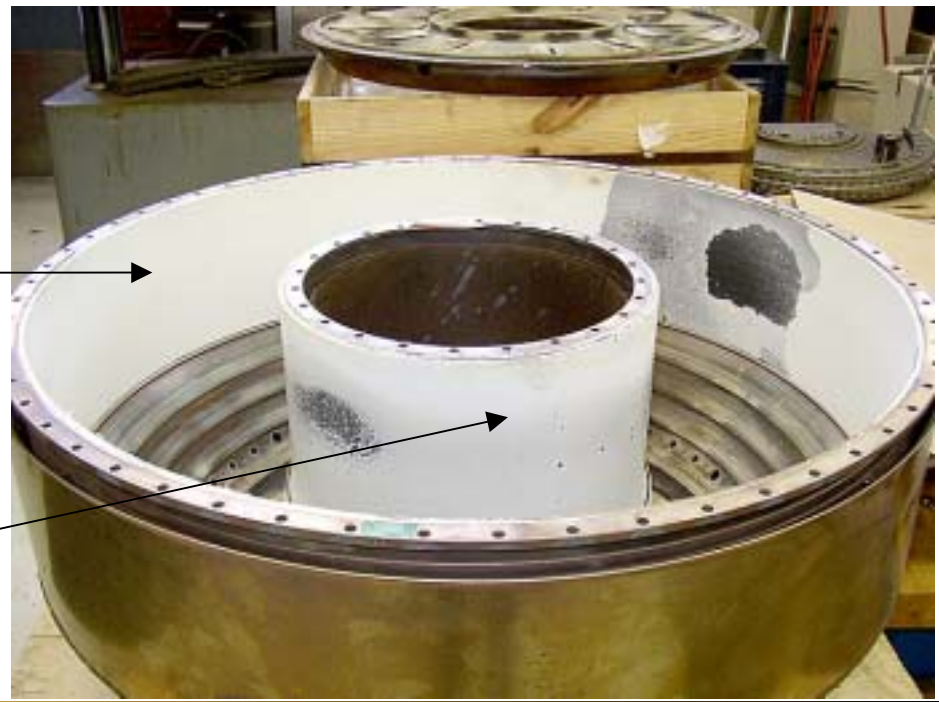
ChevronTexaco Field Test 6 - Refurbished Liners

12,373 Total Hours of Operation

Malden Mills Test 1	7238 Hours
Texaco Test 6	5135 Hours

Outer Liner 3 Layer EBC
Si/Mullite+BSAS/BSAS EBC

Inner Liner 2 Layer EBC
Si/BSAS EBC



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CFCC Durability Testing - Task 1A

ChevronTexaco Field Test 7 - Oxide/Oxide CMC Liner

Borescope - Hybrid CMC, 3384 hrs

- Began May 16, 2003
- Outer Liner - NIST ATP Program – CMCs for Advanced Engine Components
  - Hybrid CMC: Oxide/Oxide + Friable Graded Insulation (ATK COI Ceramics/ Siemens Westinghouse Power Corp.)
- Inner Liner - CSGT Program
  - HACI Hi-Nicalon/Enhanced SiC CVI with SiC Seal Coat, 3-layer EBC
- Over 4000 hours, 25 starts
- Hybrid CMC in Excellent Condition

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CFCC Durability Testing - Task 1A

Malden Mills - Field Test 3

- Test initiated in July 2002
- Combustor removed in July 2003
- 8368 hours, 32 starts
- CFCC SiC/SiC Liner Selection
  - GE PSC Tyranno/SiC-Si MI
  - No SiC Seal Coat
  - First MI Outer Liner
  - Minimize CVI Tool Marks
- Enhanced EBC - SAS

Outer Liner
3 Layer: Si/Mullite+SAS/SAS EBC

Inner Liner
2 Layer: Si/SAS EBC

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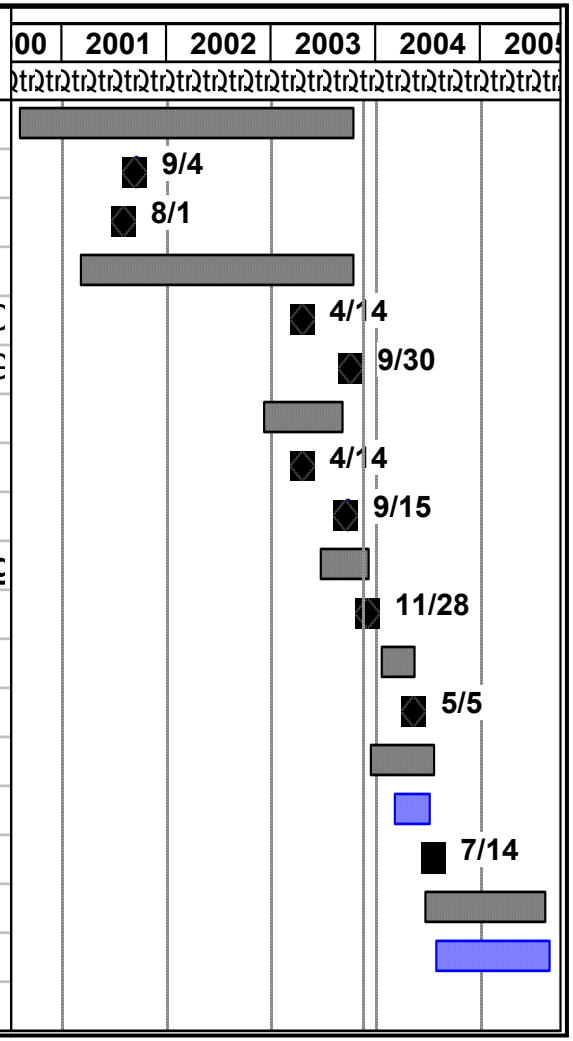
Program Schedule

Item	Task Name
1	**TASK 1 - Concept Design and Evaluation**
2	Subtask A - Market Assessment
3	DOWNSELECT FOR SUB-SCALE SYSTEM TESTING
4	**TASK 2 - System optimization (sub-scale test)**
5	Start EARLY ENGINE TEST (MOST ENCOURAGING TEC
6	DOWNSELECT OPTIMUM TECHNOLOGY MIX FOR ENG
7	**TASK 3 - Turbine modifications**
8	GAS TURBINE MODIFIED TO ACCEPT NEW SYSTEM
9	Subtask B - Commercialization plan
10	**TASK 4A - System fabrication and test (preliminary desig**
11	SYSTEM VALIDATED FOR ENDURANCE TEST
12	**TASK 4B - System fabrication and test**
13	SYSTEM VALIDATED FOR ENDURANCE TEST
14	**TASK 5A - Pre-commericial Demo, 1,000hrs**
15	Endurance Test (1000 hrs)
16	DATA FROM 1000 hr ENGINE AT SOLAR
17	**TASK 5B - Pre-commericial Demonstration**
18	Field evaluation (4,000+hrs)
19	VERIFICATION OF ADVANCED MATERIAL SYSTEM



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2003 Milestones Accomplished

- **Early Engine Demonstration with Advanced TBC** — **April 2003**
- **Down-selected TBC for 4000 hr engine demonstration** — **July 2003**
  - **40 mil Solar Advanced TBC**
- **ODS injector tips fabricated** — **June 2003**
- **ODS brazing studies completed** — **July 2003**
- **Commercialization Plan Completed (Subtask B)** — **Sept. 2003**
- **Complete 8000 hrs field test of Tyranno liner** — **July 2003**
  - **Advanced SAS EBC**
- **Over 4000 hours field test of Oxide/Oxide/FGI CMC** — **Oct. 2003**

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2004 Milestones Planned

- Complete 0.040” advanced TBC Single Injector test — Nov. 2003
- Coat full scale liner with advanced 40-mil TBC — Jan. 2004
- Start 4000 hr engine test advanced 40-mil TBC liner — May 2004
  - Mercury 50 field demonstration site
- Fabricate ODS injector tips — Mar. 2004
- Rig and In-house Engine test ODS injector tip — July 2004
- Engine test of MI CFCC liner with EBC — July 2004
  - Goodrich 3D slurry cast, GE PSC pre-preg
- Continue testing of Current CFCC liners — Ongoing
  - Advanced SAS EBC liner
  - Oxide/Oxide/FGI liner

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Key Technical Barriers & Strategies to Overcome

Combustor Liners

- Advanced TBC appears very promising
  - No key barriers identified
  - Need to demonstrate 30,000 hour life

Injector Tips

- Must demonstrate repeatable ODS material properties
  - Working with suppliers to resolve issues
  - Evaluating alternate ODS alloys as well as other materials
- ODS Alloy Attachment Concepts must be proven
  - Demonstrate in long term durability test

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Key Technical Barriers & Strategies to Overcome

CFCC Combustor Liners

- **Need to reduce cost of CFCC liners**
  - **Lower cost fibers, lower fiber volume**
  - **Reduce EBC cost**
  - **Oxide/oxide system**
- **Need to demonstrate 30,000 hr EBC life**
  - **Continue field test of 3 layer SAS EBC system**
  - **Evaluate alternate EBC systems if needed**

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Project Risks

- **Completion of 4000-hour test of ODS injector tip by Sept. 2005**
  - **Material processing issues must be resolved**
  - **Fabrication and attachment must be proven**
  - **Must complete single injector rig test prior to engine demonstration**
  - **Injector tips can be exchanged in the field with minimal interruption**
  - **Alternate solutions to injector tip durability being evaluated**

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Impact of Project on Distributed Energy Program

- **By reducing life cycle costs, the Mercury 50 gas turbine will be more attractive to the distributed power generation and co-generation market. As the market penetration of the Mercury 50 expands in the near- and mid-terms, the U.S. will benefit from:**
  - **Single digit NOx and CO emissions**
  - **Reduced CO_2 emissions due to the growth in co-generation in the near-term and the use of high efficiency gas turbine systems in the mid-term**
  - **Lower cost electricity as the benefits of distributed power generation are realized**
  - **More efficient use of natural gas in the U.S. and a reduced reliance on imported oil**
  - **A more robust electric power infrastructure through distributed power generation**

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Collaborations/Leveraging of Funds

- DOE Advanced Turbine Systems Program
- DOE Ceramic Stationary Gas Turbine Program
- DOE Continuous Fiber Ceramic-Matrix Composite Program
- South Carolina Institute for Energy Studies - AGTSR/UTSR Programs
- NASA EPM and UEET Programs
- United Technologies Research Center
- National Laboratory Support: ORNL and ANL

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Collaborations/Leveraging of Funds

- GE Power System Composites and Global Research Center
  - DOE Advanced Materials Program
- Subcontractor Cost Share - Goodrich Corporation
- NIST Program
  - ATK COI Ceramics/Siemens Westinghouse Power Corp
- End User Contribution
  - Chevron/Texaco, Malden Mills, Mercury 50 Field Demonstration Site

Summary

Advanced TBC

- Increased predicted liner life from 18,000 to over 30,000 hours through advanced TBCs
- Advanced 40 mil TBC system significantly exceeds cyclic life of baseline 25 mil TBC system
- Coated sub-scale cans for single injector rig testing
- Down-selected to Solar 40-mil advanced YSZ TBC for liner application and 4000 hr field demonstration

ODS Injector Tip

- Down-selected to ODS for injector tip application
- Developed acceptable brazing methods for ODS rings
- ODS material property issues are being addressed

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Summary

CFCC Durability Testing

- SiC/SiC CFCC Liners Have Been Tested for over 59,000 Hours in Field Testing at the ChevronTexaco and Malden Mills Sites
- Over 15,000 hours on One Set of Liners Coated with an EBC
- Over 12,000 hours on refurbished liners/EBC previously tested for 7238 hrs
- Over 8000 hrs on Tyranno liner with Advanced SAS EBC
- Over 4000 hours on Hybrid Oxide/Oxide CMC + Friable Graded Insulation
- SiC/SiC CFCC Liners Have Consistently Reduced Gas Turbine Emissions of NOx and CO

Submitted Subtask B - Commercialization Topical Report

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Advanced Materials for Mercury 50 Gas Turbine Combustion System

Questions?